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DRAINMOD-GIS: A lumped parameter watershed scale drainage and water quality model

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Abstract

A watershed scale lumped parameter hydrology and water quality model that includes an uncertainty analysis component was developed and tested on a lower coastal plain watershed in North Carolina. Uncertainty analysis was used to determine the impacts of uncertainty in field and network parameters of the model on the predicted outflows and nitrate–nitrogen loads at the outlet of the watershed. The model, which links DRAINMOD field hydrology and a spatially distributed routing model using a kernel function, accurately predicted the outlet flows and nitrate–nitrogen loads from a lower coastal plain watershed. Model predictions were within 1% of both measured outflows and nitrate–nitrogen loads. Uncertainty analysis indicated that uncertainty in stream velocities, decay coefficient and field exports significantly contributed to the uncertainty in the predicted outlet flows, loads and mean watershed delivery ratio.

Keywords: Watershed model; DRAINMOD; Drainage; Water quality

1. Introduction

Many factors affect the cumulative impacts of land use and water management practices on the downstream hydrology and drainage water quality of a watershed. The interactions of these factors are complex, but computer simulation models can be used to integrate the

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contributions from each factor. Computer models can be used to assess the impacts of alternative land uses and management practices on productivity of agricultural and forest lands and on the quality of water at the outlet of the watersheds.

The spectrum of models used for water quality planning and assessment range from comprehensive process-based models, such as WASP4 (Ambrose et al., 1981), QUAL2E (EPA, 1987), HSPF (Johanson et al., 1981), DUFLOW (Aalderink et al., 1995), CE-QUAL-RIV1 (Dortch et al., 1990) to the conceptual and/or highly simplified lumped parameter models (Haith and Shoemaker, 1987; Reckhow et al., 1992; Johnes, 1996; SPARROW, Smith et al., 1997; Fernandez et al., 2002). The complex models are capable of simulating the impacts of the dynamics of natural processes in large watersheds on a short time scale. However, as decision tools for planners they are difficult to use due to their high input data requirements, problems in calibration in large watersheds and parameterization. In addition, the underlying uncertainties in the formulation of processes and parameterization contribute to uncertainties in predictions (Beck, 1987). Decision makers may only need planning level information on the effects of land uses and management on the watershed scale. These could be obtained easily with the use of lumped parameter models, which require minimal input data to run and are capable of accurate predictions on longer time scales (Cooper and Bottcher, 1993). When coupled with error and uncertainty analyses, lumped parameter models can provide decision makers with more information than the traditional deterministic output. Moreover, the time and effort needed to run these models are usually considerably less than that required by the application of physically based models.

This paper describes the development and evaluation of a watershed scale lumped parameter model based on DRAINMOD hydrology and water quality models. The integration of DRAINMOD and a lumped parameter water quality model with a simplified drainage canal routing and in-stream process sub-model is described. The performance of the model was evaluated considering the uncertainties of the model inputs. The model was tested with measured data from a 2950 ha watershed in the lower coastal plain of North Carolina. Results of those tests are presented and discussed.

2. Watershed scale model

The watershed scale model presented in this paper integrates the field hydrology model, DRAINMOD (Skaggs, 1978, 1999), and a generalized spatially distributed canal routing model using a response function (Moussa, 1997; Olivera and Maidment, 1999). Field hydrology is simulated with DRAINMOD and network routing is modeled with a kernel function based on the Hayami function to characterize the time of travel in the drainage network.

DRAINMOD is a field-scale, water management simulation model that characterizes the responses of the soil water regime to various surface and sub-surface water management practices. It predicts the response of the water table and soil moisture to precipitation and evapo-transpiration considering surface and sub-surface drainage under various water table control or sub-irrigation practices. The model is generally used to simulate the performance of drainage and related water table management systems over a long period of climatological data. It is suited for characterizing the hydrology of nearly level landscapes with shallow water table soils where surface and sub-surface flows are very dependent on water table depth.

DRAINMOD calculates a water balance at the soil surface and in the soil profile on a day-by-day, hour-by-hour basis. The model assumes that surface runoff occurs when the storage capacity of surface depressions is filled. Sub-surface drainage rates are calculated in one of two ways depending on whether there is surface ponding or not. The steady-state Hooghoudt equation is used to calculate the sub-surface drainage rate during non-ponded conditions. During continuous wet periods when the water table may rise to the surface, DRAINMOD uses the equation developed by Kirkham (1957) to quantify drainage rates. Infiltration is calculated by the Green–Ampt equation with parameters dependent on water table position.

2.1. Network model

The Saint Venant (SV) equations are generally accepted as an adequate representation of one-dimensional water transport in open channels and on hillslopes (Troch et al., 1994). Approaches to characterize channel flow and overland flow routing were therefore based on solutions of these equations. However, explicit analytical solutions to the SV equations are difficult to obtain, hence, researchers often resort to approximations. One approach in simplifying the SV equations is to neglect the acceleration terms, thus reducing the model to a diffusion equation (Brutsaert, 1973). If the inertial terms in the St. Venant momentum equation are neglected, one-dimensional flow in a stream segment can be modeled with the diffusion wave equation (Miller and Cunge, 1975; Lettenmaier and Wood, 1993). Neglecting lateral inflow in a stream segment, the flow in a canal segment i can be represented by

$$\frac{\partial Q_i}{\partial t} + c_i \frac{\partial Q_i}{\partial x} - d_i \frac{\partial^2 Q_i}{\partial x^2} = 0 \quad (1)$$

where x is the distance along the flow direction, t the time, Q_i is the flow at any time t and location x of segment i, c_i and d_i is the wave celerity and diffusivity, respectively. In general, most flood wave propagation in stream channels can be characterized by the diffusive wave criterion, which under certain assumptions can be reduced to a linearized form of the kinematic wave (Beven, 1979). The diffusive wave equation can be used to model backwater effects resulting from obstructions to the flow or the confluence of different branches of the network.

Hayami (1951) (as cited by Moussa, 1996, 1997) derived the linear solution to Eq. (1) for a constant c_i and d_i. For a case of a semi-infinite channel, the analytical solution to the diffusive wave equation for a constant c_i and d_i is given as (Moussa, 1996, 1997),

$$\begin{aligned} Q_i(x,t) = Q_i(0,0) + \frac{x}{2(\pi d_i)^{1/2}} \exp\left(\frac{c_i x}{2 d_i}\right) \int (Q_i(0, t-\tau) \\ - Q_i(0,0)) \frac{\exp\left\{-\frac{c_i x}{4 d_i}\left(\frac{x}{c_i \tau} + \frac{c_i \tau}{x}\right)\right\}}{\tau^{3/2}} \mathrm{d}\tau \end{aligned} \quad (2)$$

for $0 \leq x \leq l_i$, l_i is the channel length and t is time. Let $I_i(t)$ and $O_i(t)$ be the upstream and downstream flows for channel segment i, respectively, then

$$I_i(t) = Q_i(0,t) - Q_i(0,0)$$

$$O_i(t) - Q_i(l_i,t) - Q_i(l_i,0)$$

Using the expressions for $I_i(t)$ and $O_i(t)$, then Eq. (2) can be expressed as:

$$O_i(t) = \int_0^t I_i(\tau)\,K_i(t-\tau)\,\mathrm{d}\tau = I_i(t) * K_i(t) \tag{3}$$

where $K_i(t)$ is the Hayami kernel function defined as:

$$K_i(t) = \frac{l_i \exp\left\{\frac{c_i l_i}{4d_i}\left(2 - \frac{l_i}{c_i t} - \frac{c_i t}{l_i}\right)\right\}}{2(\pi d_i)^{1/2} t^{3/2}} \tag{4}$$

The kernel function given in Eq. (4) is characterized by two parameters, c_i and d_i.

For application in a spatially distributed modeling of flows in a channel network, Moussa (1997) developed a procedure for routing flows using the Hayami kernel function. A short account of the approach following Moussa (1997) is provided here, for the sake of completeness. In a watershed sub-divided into non-overlapping areas (referred to as fields), the outflow from each field is independently routed directly through the drainage network to the outlet considering its flow path. For a given field, consider its flow path to the outlet that can be divided into n channel segments. Inflow hydrograph, $I_1(t)$, for segment 1 is routed through the first segment to produce an outflow $U_1(t)$. This outflow is then used as input to the second segment producing an outflow, $U_2(t)$, which is used as input to the third segment and so on. The sequential routing is continued until the last segment to produce the outlet hydrograph (for inflow hydrograph resulting from flow for a given field), that is $U_n(t) = O(t)$.

Eq. (3) requires that $U_1(t) = I_1(t)*K_1(t)$ for segment 1, where '*' implies convolution (convolution defined by the integral). For subsequent segments, $U_i(t) = U_{i-1}(t)*K_i(t)$. The outflow at the most downstream segment of the given flow path can then be generalized as:

$$O(t) = I_i(t) * K_1(t) * K_2(t) * K_3(t) \ldots * K_n(t) \tag{5}$$

The problem considered herein is to find an equivalent kernel function, $K_e(t)$, such that Eq. (5) can be computed equivalently as $O(t) = I(t)*K_e(t)$ where

$$K_e(t) = K_1(t) * K_2(t) * K_3(t) * \ldots * K_n(t) \tag{6}$$

The convolution of several Hayami functions is not necessarily a Hayami function (Moussa, 1997). A kernel function K_e (assumed to be a Hayami function) can be approximated that satisfy Eq. (6) with parameters, c_e and d_e. Using Laplace transform and the first and second moments of the kernel function, $K(t)$, Moussa (1997) derived the equivalent parameters, c_e and d_e for a flow path as:

$$c_e = \frac{l_e}{\sum_{i=1}^{n} \frac{l_i}{c_i}} \tag{7}$$

$$d_e = \frac{c_e^3}{l_e} \sum_{i=1}^{n} \frac{l_i d_i}{c_i^3} \tag{8}$$

where $l_e = \sum_{i=1}^{n} l_i$ the total length of the flow path from the field to the outlet. For a given flow path j, then the outflow resulting from an upstream inflow $I_j(t)$ can be written as $O_j(t) = I_j(t) * K_e(t)$ where

$$K_e(t) = \frac{l_e \exp\left\{\frac{c_e l_e}{4 d_e}\left(2 - \frac{l_e}{c_e t} - \frac{c_e t}{l_e}\right)\right\}}{2(\pi d_e)^{1/2} t^{3/2}} \tag{9}$$

The watershed outflow is the sum of all outflows from each flow path.

Olivera and Maidment (1999) developed a similar spatially distributed routing model, which uses the first passage time distribution as a flow path response function. The response function of Olivera and Maidment (1999) can be shown to be equivalent to the Hayami function. The first passage time distribution has been previously used to model residence time of water in hydrologic systems (Mesa and Mifflin, 1986; Naden, 1992; Troch et al., 1994).

2.2. DRAINMOD-GIS

DRAINMOD-GIS was developed using the flow path response function described in Eq. (9) as basis for drainage network routing. The model considers spatially distributed inputs and parameters where outflows from contributing areas (non-overlapping fields) are routed directly through the drainage network to the outlet. The two parameters routing response function model given in Eq. (9) route flows from each field to the watershed outlet according to its flow path. The flow path of each field is determined from the geometry of the drainage network of the watershed. The outflow at the outlet is obtained as the sum of the routed hydrograph from all fields in the watershed. This routing framework enables the identification of the contribution of the response of each field in the overall response at the outlet of the watershed. This also enables quantification of the delivery ratio of a water quality parameter, i.e. the fraction of a water quality parameter exported from a field that is delivered to the outlet. Knowledge of the spatial distribution of delivery ratios is important in targeting the application of management practices spatially (on a field by field basis) to minimize the impact on water quality or pollutant load at the watershed outlet.

The hydrology model, DRAINMOD, simulates water losses from the field areas either under controlled or conventional drainage. For each field, these water losses are routed to the field outlet using an instantaneous unit hydrograph and eventually routed through the drainage network to the watershed outlet using response function for its defined flow path. Eq. (9) is parameterized by the corresponding flow path characteristics. For water quality, an exponential decay model characterizes the attenuation of the water quality parameter as it travels along the flow path. Eq. (9) was modified to account for the nutrient loss as

$$K'_e(t) = \frac{l_e \exp\left\{\frac{c_e l_e}{4 d_e}\left(2 - \frac{l_e}{c_e t} - \frac{c_e t}{l_e}\right)\right\}}{2(\pi d_e)^{1/2} t^{3/2}} \exp(-k_c t) \tag{10}$$

where k_c is the decay coefficient and $K'_e(t)$ is the response function for the water quality parameter.

Using Manning's formula for the mean velocity of a turbulent uniform flow in open channels

$$V = \frac{1}{n}\sqrt{S}R^{2/3} \tag{11}$$

where V is the mean velocity, R the hydraulic radius, S the channel slope and n is the roughness coefficient, then for a trapezoidal channel, c_e can be expressed as:

$$c_e = \frac{dQ}{dA} = \left[\frac{5}{3} - \frac{4}{3}R\frac{\sqrt{1+z^2}}{b+2zy}\right]V \tag{12}$$

where y and z are the flow depth and side-slope, respectively. For a given flow path, the parameter c_i and d_i for each channel segment i in the flow path can be estimated using Eqs. (11) and (12) as

$$c_i \approx c_m\sqrt{\frac{S_i}{S_m}} \quad \text{and} \quad d_i \approx d_m\frac{S_m}{S_i} \tag{13}$$

where S_i and S_m are the slope of channel segment i and the mean slope of all segments in a flow path, respectively. The parameters c_m and d_m for a flow path are parameters that will have to be calibrated. These parameters can be generalized for the whole watershed, as a first approximation, c_m can be taken as V.

3. Methods

3.1. Site description

The site is a 2950 ha drained forested watershed (S4 in Fig. 1) located in Weyerhaeuser Company's Parker Tract in Washington country in eastern North Carolina. The S4 watershed is part of a larger, intensively instrumented (10,000 ha) mixed land use watershed. Both organic (primarily Belhaven and Pungo series) and mineral soils (poorly drained Portsmouth and Cape Fear series) are present in the watershed. The drainage system is typical for the lower Coastal Plain with field ditches 100 m apart emptying into collector canals at about 800 m intervals which outlet to main canals about 1600 m apart. The spacing of main and collector canals may vary across the site; they are shown in Fig. 1. Surface cover is characterized by second growth mixed hardwood and pine forest, and loblolly pine plantation at various ages and stages.

Several gauging and sampling stations within the watershed (Fig. 1) record flow and sample drainage waters for water quality. Gauging stations are located at four field drainage outlets (F3, F5, F6, and F7), three on the main drainage canals (S1, S2, and S3) and at the outlet of watershed (S4). Instrumentation at the automatic stations includes sharp crested 120° V-notch weirs, water level recorders, automatic samplers and microprocessors to store data and control the samplers. A velocity meter with ultrasonic Doppler technology (STARFLOW, Unidata America) is also installed at the outlet of the watershed. More details of the watershed are given by Amatya et al. (2004).

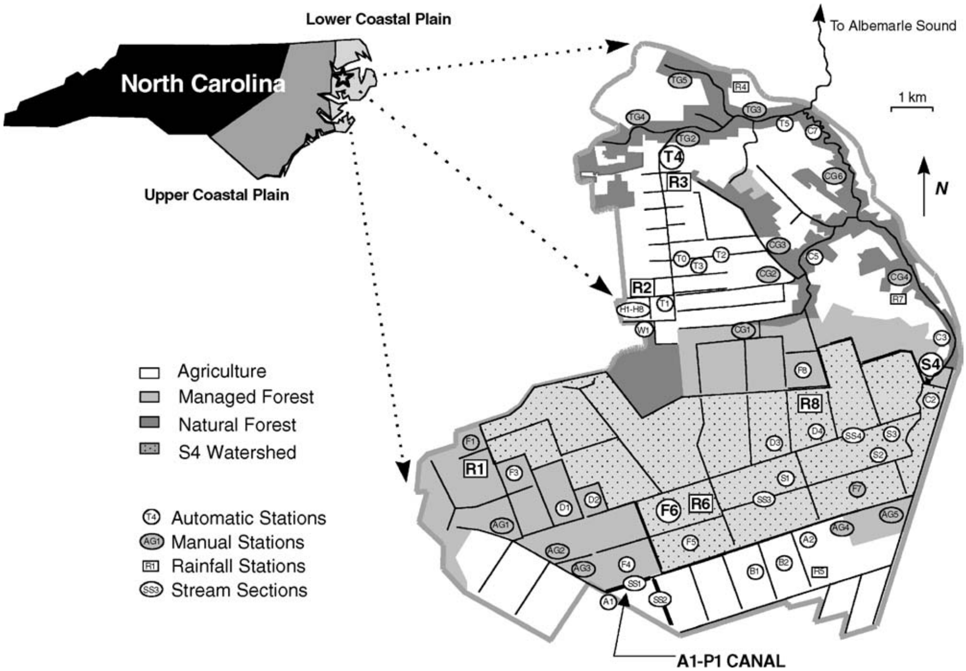

Fig. 1. Diagram of the study area near Plymouth, NC.

3.2. Watershed modeling

The watershed was divided into 27 fields with the drainage network discretized into 46 canal segments (Fig. 2). The fields were assumed homogenous with respect to soils, surface cover and water management practices. Field areas, stream lengths, dimensions of canals,

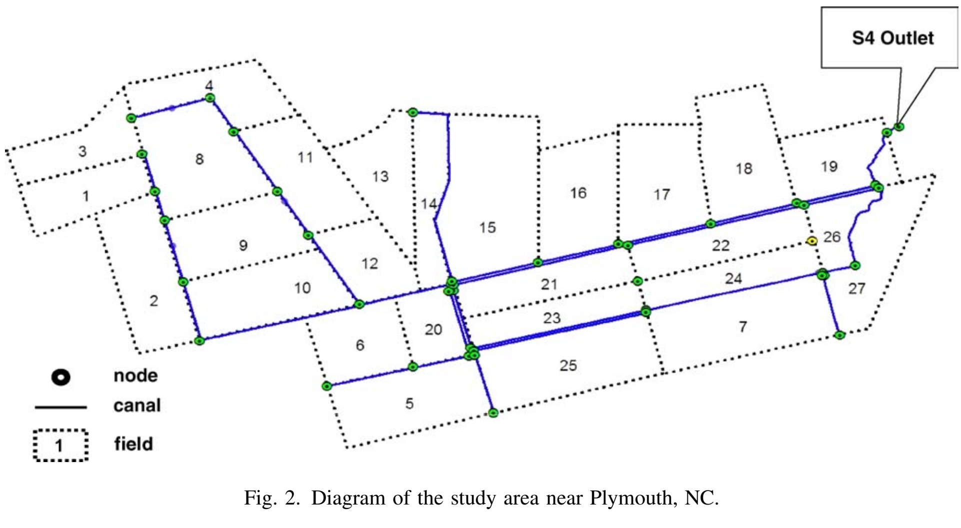

Fig. 2. Diagram of the study area near Plymouth, NC.

Table 1
Properties of fields in the S4 watershed

Field	Landuse	Soils	Area (m^2)
1	6-year loblolly pine	Cape Fear s.l.	790908
2	4- and 18-year loblolly pine	Cape Fear s.l.	1337255
3	12-year loblolly pine	Cape Fear s.l.	791073
4	4–11-year loblolly pine	Cape Fear s.l.	905875
5	12-year loblolly pine	Belhaven Muck	1277208
6	4-year loblolly pine	Belhaven Muck	897962
7	55–75-year mixed hardwood	Belhaven Muck	1605975
8	15-year loblolly pine	Cape Fear s.l.	1432112
9	15-year loblolly pine	Cape Fear s.l.	1112771
10	8-year pine and mixed hardwood	Belhaven Muck	1290504
11	4- and 17-year loblolly pine	Cape Fear s.l.	1112042
12	7–8-year loblolly pine	Belhaven Muck	787356
13	Loblolly pine and mixed hardwood	Porstmouth s.l.	972640
14	10–14-year loblolly pine	Belhaven Muck	717254
15	50–70-year mixed hardwood	Belhaven Muck	2052072
16	50-year mixed hardwood	Belhaven Muck	1221238
17	4-year loblolly pine	Belhaven Muck	1302435
18	18-year loblolly pine	Cape Fear s.l.	1367641
19	10–15-year loblolly pine	Porstmouth s.l.	850874
20	16-year mixed hardwood	Belhaven Muck	595025
21	4-year loblolly pine	Belhaven Muck	895534
22	68-year mixed hardwood and 9-year pine	Belhaven Muck	942952
23	683–78-year mixed hardwood	Belhaven Muck	768318
24	68-year mixed hardwood and 9-year pine	Belhaven Muck	793174
25	6-year loblolly pine	Belhaven Muck	1584969
26	6-year loblolly pine	Wasda Muck	455962
27	11–23-year loblolly pine	Wasda Muck	1199823

field and canal bed elevations were obtained from field surveys and topographic maps. Field characteristics are shown in Table 1. Soil properties of the dominant soil series in each field were obtained from published values as reported in Skaggs and Nassehzadeh-Tabrizi (1986) and from measured data at fields F3 and F6 (Diggs, 2004) (Table 2). Rainfall and temperature from the R6 station (Fig. 1) were used in the DRAINMOD simulations. The model was calibrated with the 1996–1997 flow and nitrate–nitrogen load data and validated with the 1998–2000 flow and nitrate–nitrogen data.

Drainage outflows from each field, as predicted by DRAINMOD, were treated as inflows into the network at designated nodes (Fig. 2). Flows from the field outlets were

Table 2
Soil hydraulic parameters of the S4 watershed

Parameters	Belhaven	Cape fear	Portsmouth	Wasda
Impermeable layer (cm)	270	300	240	200
Hydraulic conductivity (cm/hr)	400	400	50	20
Saturated water content (cm^3/cm^3)	0.73	0.48	0.37	0.76
Wilting point (cm^3/cm^3)	0.45	0.22	0.13	0.45
Percentage of area	58	30	6	6
Number of fields	15	8	2	2

routed on an hourly time step to the watershed outlet using the response function. In the same manner, nitrate–nitrogen loads were routed to the outlet using an exponential decay process. Water quality data (nitrate–nitrogen) collected from 1996 to 1997 composite and grab samples from five experimental fields in and around the S4 watershed were used to develop the export loads from the individual fields using a multiple regression model. Daily nitrate–nitrogen loading rate were expressed as a function of daily flows and the previous day nitrate–nitrogen loading rate given as

$$\log \mathrm{NO_3}(t) = a + b\log(Q_t) + c\log(\mathrm{NO_3}(t-1)) + d\log(I) \tag{14}$$

where $\mathrm{NO_3}(t)$ (kg/(ha day)) is nitrate–nitrogen loading rate at day t, Q (m^3/s) is the mean daily flow rate at day t, $\mathrm{NO_3}(t-1)$ (kg/(ha day)) is the nitrate–nitrogen loading rate at day $t-1$ and I is an index variable which is 1 or 10 for mineral and organic soil, respectively. The regression model accounts for the persistence of daily loading rates.

The routing model requires stream velocities to derive the parameters of the flow path response function. For this study, stream velocities were obtained from simulations using the DRAINMOD-DUFLOW model (Fernandez et al., 2004). The velocities were spatially and temporally average. In the absence of detailed knowledge of the hydraulics of the system, one can use a mechanistic model to predict characteristic velocities of the drainage canals. For routine application of the watershed model, the stream velocities and the dispersion coefficient are parameters that need to be calibrated. Stream velocities can also be obtained from measured values.

3.3. Statistical analysis

The adequacy of the model to predict the daily and monthly flows and nitrate loads at the outlet of the watershed was determined using a number of different statistical measures in the literature. The most common measure is the coefficient of determination, r^2 or alternatively the correlation coefficient, r. Legates and McCabe (1999) also recommends using the modified coefficient of efficiency, E', and the index of agreement, d', defined as

$$E' = 1.0 - \frac{\sum_{i=1}^{n} |O_i - P_i|}{\sum_{i=1}^{n} |O_i - \bar{O}'|} \tag{15}$$

$$d' = 1.0 - \frac{\sum_{i=1}^{n} |O_i - P_i|}{\sum_{i=1}^{n} (|P_i - \bar{O}| + |O_i - \bar{O}|)} \tag{16}$$

where O_i are the measured values, P_i the model predictions and $\bar{O}$ is the average of measured values. The coefficient of efficiency defined above is a modification of the Nash–Sutcliffe coefficient of efficiency (Nash and Sutcliffe, 1970) where it also ranges from $-\infty$ to 1, where 1 is perfect model prediction. The use of absolute error gives appropriate weighting to the model prediction errors, hence, the modified coefficient of efficiency and index of agreement are not biased towards extreme values. Legates and McCabe (1999) indicated that the original coefficient of efficiency and index of agreement is overly sensitive to extreme values. The mean absolute error (MAE) (defined as $\frac{1}{n}\sum_{i=1}^{n}|O_i - P_i|$) and the root mean square error (RMSE) are also reported in this paper.

3.4. Uncertainty analysis

Uncertainty analysis was used to quantify the precision of the model predictions. The procedure for performing uncertainty analysis of the watershed scale model follows that proposed by Haan and Skaggs (2003). Field parameters identified by Haan and Skaggs (2003) as the most sensitive and influential to field water losses were used in this study. For controlled and conventional drainage, the lateral saturated hydraulic conductivity (CONK) used in DRAINMOD to calculate sub-surface flow and the maximum surface storage (STMAX) (surface depressional storage that must be filled before surface runoff occurs) were found to be the most influential in characterizing the variability in surface and sub-surface flows (Haan and Skaggs, 2003). For drainage routing and water quality modeling, the impact of the uncertainty in dispersion coefficient (DISP), nutrient decay coefficient (KC), stream velocity (VEL) and field export load (EXPC) were investigated.

Means, variances, coefficients of variation and the probability density functions for the field and network parameters were obtained from literature values (e.g. Haan and Skaggs, 2003) and from measured values in the watershed. It was assumed that the parameters have negligible correlations.

Latin Hypercube sampling (LHS) (Salas and Shin, 1999) was used to generate random samples (500 samples) of the different field and network parameters. LHS is a stratified sampling approach that allows efficient estimation of the statistics of the output. In LHS, the probability distribution of each basic variable is sub-divided into N ranges each with a probability of occurrence equal to $1/N$. Random values of the basic variables are generated such that each range is sampled only once. Output statistics and distributions of the output variables are then approximated from the sample of N output values. In this paper, we follow the procedure of performing uncertainty analysis using LHS as described by Salas and Shin (1999):

1. For an input x, obtain n uniform random numbers, $U_1, U_2, \ldots, U_n$ in the range of 0–1.
2. Define $P_i = (1/n)[U_i + (i - 1)]$ $(i = 1, \ldots, n)$. Then, P_i falls exactly within each of the n intervals $(0, 1/n), (1n, 2n), \ldots, ((n - 1)/n, 1)$.
3. From the cumulative distribution function $F(x)$ of the input x, determine the values $x_i = F^{-1}(P_i)$ $(i = 1, \ldots, n)$. Then, $x = [x_1, x_2, \ldots, x_n]$ is the sample vector of the stochastic input x.
4. Perform random permutation of the set $(x_1, x_2, \ldots, x_n)$ obtained in step 3.
5. Repeat steps 1–4 for all inputs.

The procedure assumes that all inputs were independent. However, in the case of correlated inputs, the joint distributions of the inputs have to be considered.

4. Results and discussion

4.1. Flow

The watershed model was calibrated with the 1996–1997 data and validated with the 1998–2000 flow data measured at the outlet of S4. The temporal trend and magnitudes of daily and monthly flows predicted by the model closely agreed with the observed data as shown in Figs. 3 and 4. Predicted daily and monthly outflows at the watershed outlet were in good agreement with the measured values. Except for the large events during the passage of tropical storms in 1996 and the under-prediction of the events in early winter (1996) and spring (1997), the predicted daily flow time series (Fig. 3) indicate that peaks and recessions of the flow are accurately simulated. Differences between observed and predicted peaks and hydrograph recessions are attributed to the fact that the model, as applied, did not consider the effects of in-stream control structures. Measurement weirs were submerged during the tropical storms and hence the measured flow data could also have been underestimated for those periods. Moreover, errors in estimating potential evapotranspiration could have contributed to the under-prediction of the total flow during the calibration period. A similar pattern was observed during the validation period when peak flows during large rain events were over-predicted.

On an annual basis (Table 3), the prediction errors ranged from under-prediction of 9% (1997) to over-prediction of 4% (1999). On average, the mean daily absolute error was 0.4 mm for both the calibration and validation periods. Average absolute error for 1997 was the lowest for all the years. Prediction errors for the cumulative outflows for both periods were within 1%. For the 5-year period, the cumulative outflow was predicted with prediction error of less than 1% and mean daily absolute error of 0.4 mm. Predicted annual runoff ratios (ratio of outflow to rainfall) accurately match the measured runoff ratios. Table 4 summarizes the statistics of comparison between the predicted and measured outflows. The statistics are generally acceptable for both the daily and monthly data. The modified Nash–Sutcliffe coefficients and indices of agreement are within satisfactory

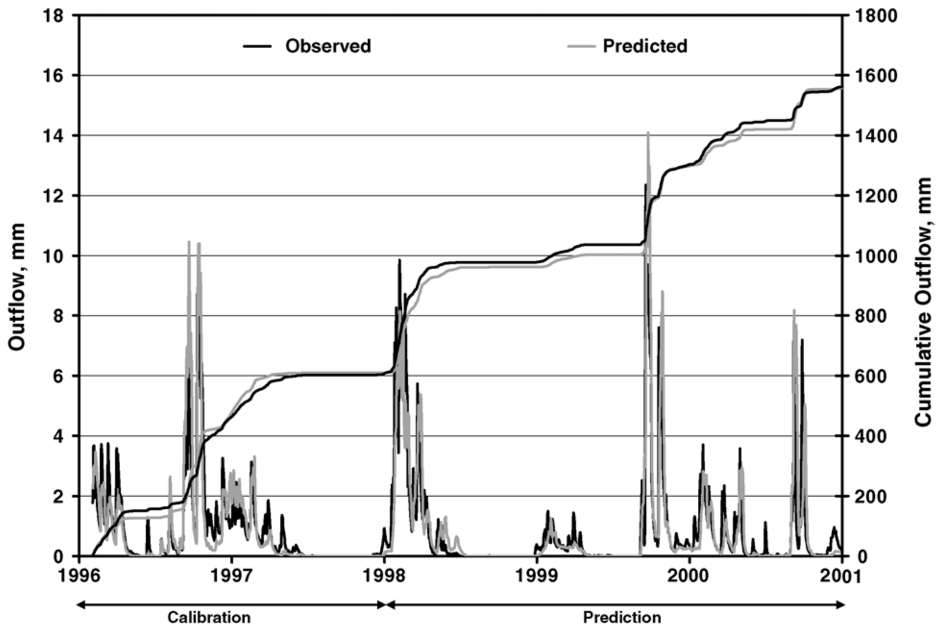

Fig. 3. Observed and predicted daily and cumulative daily outflows at S4.

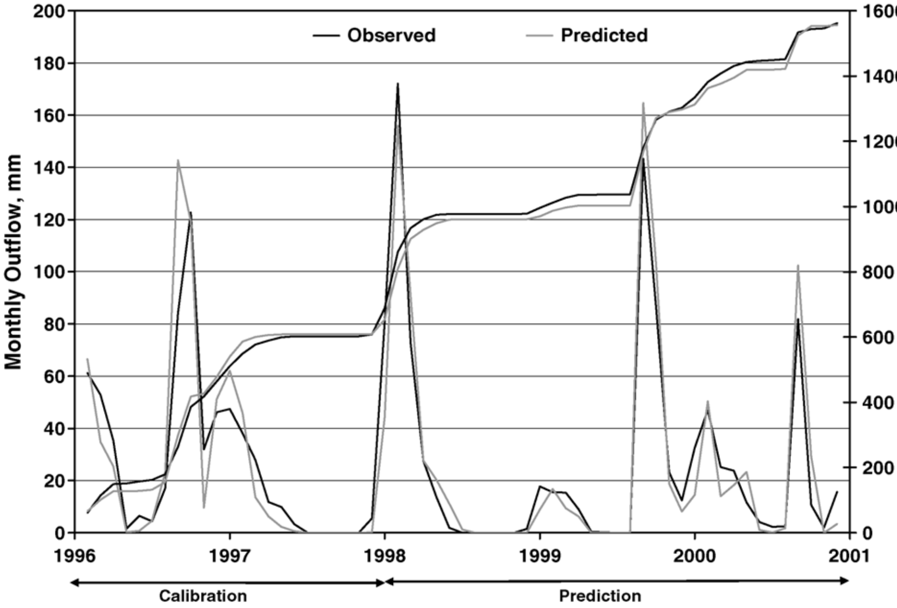

Fig. 4. Observed and predicted monthly and cumulative monthly outflows at S4.

Table 3
Summary of measured and predicted annual outflows at the outlet of the S4 watershed

(a)

	Rainfall (mm) (*R*)	Measured (mm) (*O*)	Predicted (mm) (*P*)	Error (mm)	Prediction error (%)	Mean daily Abs error (mm)
1996	1409	464	478	14	3.0	0.6
1997	957	144	131	−13	−9.0	0.2
1998	1275	370	352	−18	−4.9	0.4
1999	1382	324	337	13	4.0	0.4
2000	1220	259	258	−1	−0.4	0.5
1996–1997	2367	608	609	1	0.3	0.4
1998–2000	3877	954	947	−7	−0.7	0.4
1996–2000	6244	1562	1556	−6	−0.4	0.4

(b)

	Rainfall (mm)	PET (mm)	Measured runoff ratio (%) (*O*/*R*)	Predicted runoff ratio (%) (*P*/*R*)
1996	1409	887	33	34
1997	957	882	15	14
1998	1275	936	29	28
1999	1382	993	23	24
2000	1220	962	21	21
1996–1997	2367	1769	26	26
1998–2000	3877	2890	25	24
1996–2000	6244	4659	25	25

Table 4
Summary of statistics for goodness of fit of the predicted watershed outflows

	Calibration 1996–1997	Prediction 1998–2000
Daily		
Observed mean (mm)	0.87	0.87
Predicted mean (mm)	0.87	0.86
MAE (mm)	0.40	0.40
RMSE (mm)	0.80	1.00
Modified Nash–Sutcliffe	0.56	0.60
Modified index of agreement	0.80	0.80
Pearson correlation	0.88	0.85
Monthly		
Observed mean (mm)	26.4	26.5
Predicted mean (mm)	26.5	26.3
MAE (mm)	8.4	7.4
RMSE (mm)	14.9	11.2
Modified Nash–Sutcliffe	0.66	0.74
Modified index of agreement	0.84	0.87
Pearson correlation	0.93	0.97

range (>0.5). Similarly, the Pearson correlation coefficients were high (>0.80) which indicate satisfactory goodness of fit between the predicted and measured daily outflows. The correlation coefficients were even higher for the comparison of the monthly values. Fig. 5 plots predicted versus observed monthly flows. The plot shows relatively good agreement (with $R^2 = 0.93$ and slope = 1.01, close to 1.0) with increased scatter for higher

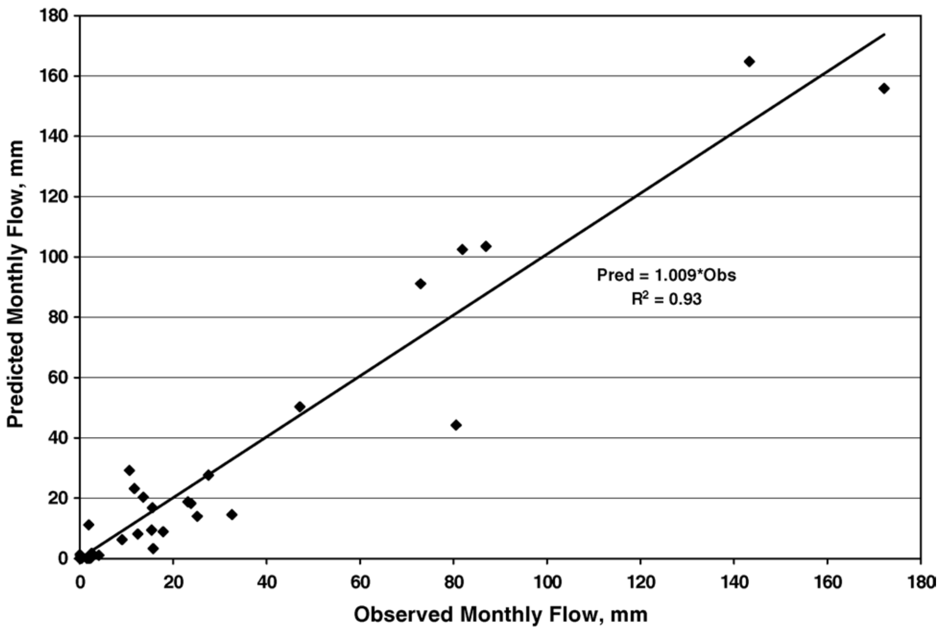

Fig. 5. Observed and predicted monthly outflows at S4 for 1998–2000.

flows. Fernandez et al. (2004) simulated the S4 watershed using two models (DRAINMOD-W and DRAINMOD-DUFLOW) based on the numerical solution to the full SV equations. Simulations show that the predictions of DRAINMOD-GIS for the same period are not statistically different from the predictions of either DRAINMOD-W or DRAINMOD-DUFLOW.

4.2. Nitrate–nitrogen load

Measured nitrate concentrations for 1996–2000 were used to test the water quality component of the models. Minimal calibration was conducted. Calibration was used primarily to determine the optimal decay coefficient that would give the minimum error in predicted cumulative nitrate load at the outlet of the watershed. A calibrated decay parameter of 0.12/day was used. Export nitrate–nitrogen loads were obtained from a regression model (Eq. (14)) that relates the measured daily nitrate load with the daily flow and the previous day nitrate load from five fields (F3, F5, F6, F7, and F8) in and around the watershed. Fig. 6 shows the comparison of the predicted versus observed nitrate loading rates using the regression equation. The daily nitrate loading rates from the field is predicted well by the model ($R^2 = 0.98$).

Figs. 7 and 8 show the comparison of the time series of the measured and predicted daily and monthly nitrate–nitrogen loads for the watershed. As shown in Table 5, the cumulative nitrate load was under-predicted by 2.9% during the calibration period and over-predicted by 1.2% for the validation period. On an annual basis, the prediction errors ranged from an

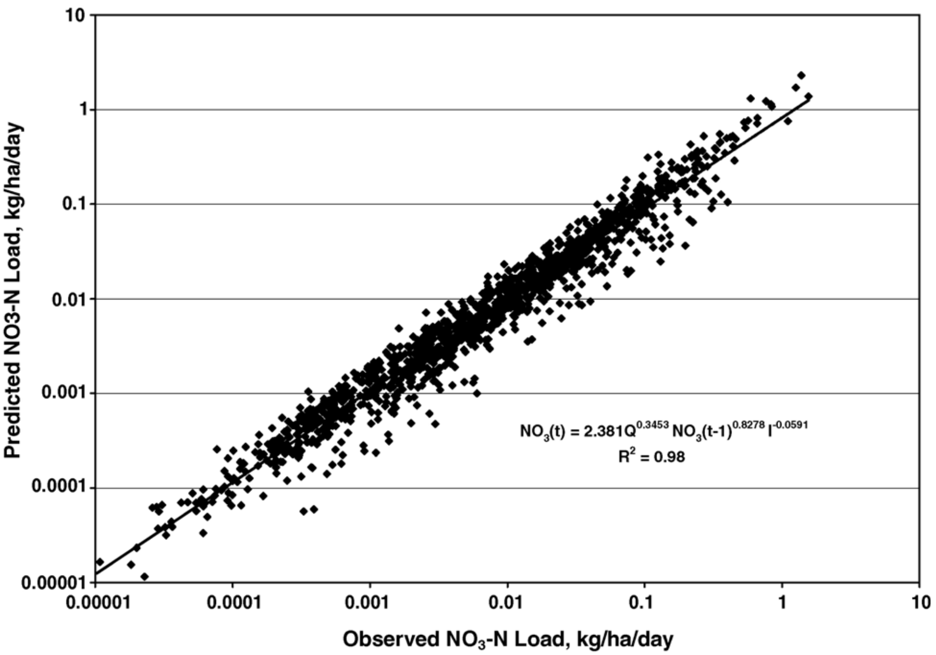

Fig. 6. Observed and regression predicted daily nitrate load for 1996–1997.

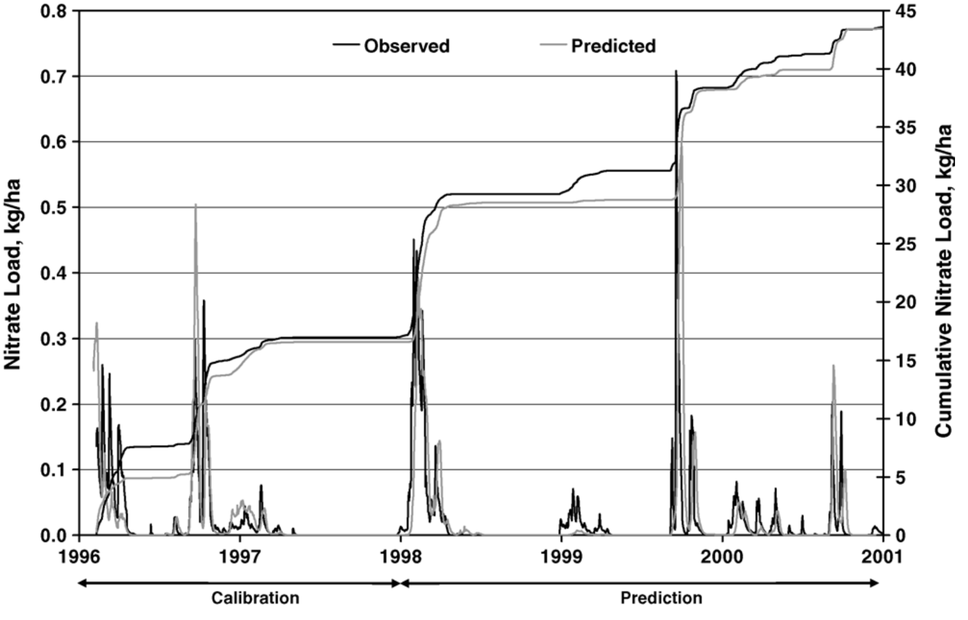

Fig. 7. Observed and predicted daily and cumulative daily nitrate–nitrogen load at S4.

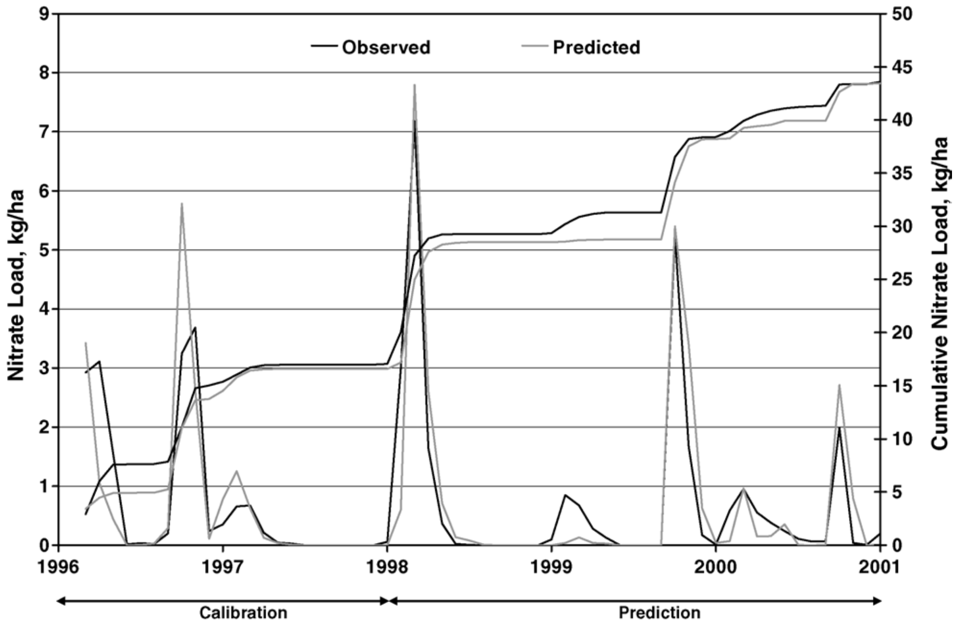

Fig. 8. Observed and predicted monthly and cumulative monthly nitrate–nitrogen load at S4.

Table 5
Summary of measured and predicted annual nitrate load at the outlet of the S4 watershed

	Measured (kg/ha)	Predicted (kg/ha)	Prediction error (%)	Mean daily Abs error (kg/ha)
1996	15.38	14.53	−5.6	0.033
1997	1.68	2.06	−22.6	0.004
1998	12.30	11.93	−3.0	0.020
1999	9.03	9.70	7.4	0.031
2000	5.20	5.22	0.3	0.015
1996–1997	17.06	16.59	−2.9	0.018
1998–2000	26.52	26.84	1.2	0.023
1996–2000	43.59	43.43	−0.4	0.020

under-prediction of as much as 23% (1997) to an over-prediction of 7% (1999). Although, the prediction error for 1997 was the highest, the corresponding mean daily absolute error was the lowest over the 5-year period. Overall for the 5-year period, the cumulative nitrate–nitrogen load was only under-predicted by 0.4% with a mean daily absolute error of 0.02 kg/ha.

Errors in the predictions of the nitrate–nitrogen loads were probably due to errors in the predicted loads at the field edge. Loading events in 1998–1999 mostly resulted from flow events after an extended dry period. Analysis of field data indicated that nitrate concentrations were generally high at the onset of such events due to the flushing of nitrate–nitrogen that had been mineralized during the extended dry period. This phenomenon is not considered in the dynamics of the model. A large percentage of the soils (70%, Table 1) in the watershed are organic, hence, there is high potential for mineralization of the organic nitrogen. However, on a long-term basis, the model adequately predicted the nitrate–nitrogen loads of the watershed.

Table 6 summarizes statistics of comparison between the predicted and observed daily and monthly nitrate–nitrogen loads. In contrast to the flow simulation, the modified Nash–Sutcliffe coefficient for the daily predictions is barely within the satisfactory range. However, the modified index of agreement is within the satisfactory range. Statistics for the monthly comparisons are generally higher. Fig. 9 shows the comparison of the predicted versus observed monthly loads for the validation period. The plot shows relatively good agreement (with $R^2 = 0.87$ and slope = 1.024, close to 1.0). As in the monthly flow predictions, there was greater scatter for the higher loading rates. This could be explained partly by the large standard errors of prediction. The high coefficient of determination is probably biased since the regression line tends to fit the extreme values (Legates and McCabe, 1999). The coefficient of determination is overly sensitive to outliers than to observations near the mean. This oversensitivity to outliers leads to bias toward the extreme events (Legates and Davis, 1997). Overall, for daily and monthly load comparisons, the model predictions were in good agreement with the measured nitrate–nitrogen loads of the watershed.

DRAINMOD-GIS allows the determination of the contribution of individual field exports to the overall watershed export at the outlet. The individual contribution of each field export is quantified by a delivery ratio. The delivery ratio (DR) is defined for a given field as the fraction of the load that is delivered to the outlet of the watershed. The DR (ranges from 0 to 100%) is an expression of the in-stream attenuation of the field exports

Table 6
Summary of statistics of goodness-of-fit of the predicted nitrate–nitrogen load at the outlet of S4

	Calibration 1996–1997	Prediction 1998–2000
Daily		
Observed load (kg/ha)	0.025	0.024
Predicted load (kg/ha)	0.024	0.026
MAE (kg/ha)	0.017	0.022
RMSE (kg/ha)	0.05	0.07
Modified Nash–Sutcliffe	0.49	0.35
Modified index of agreement	0.74	0.69
Pearson correlation	0.69	0.58
Monthly		
Observed load (kg/ha)	0.742	0.737
Predicted load (kg/ha)	0.721	0.746
MAE (kg/ha)	0.381	0.327
RMSE (kg/ha)	0.108	0.091
Modified Nash–Sutcliffe	0.59	0.65
Modified index of agreement	0.80	0.83
Pearson correlation	0.83	0.93

and it depends on flow rates and travel times in the canals. Fig. 10 shows the average annual delivery ratio for each field. It shows the spatial variability of DR within the watershed. Plots of DR can be used to target the application of management practices. For the S4 watershed, the mean delivery ratio ranges from 36% from the most distant field from the outlet to 99% for a field near the outlet. Assuming the same loading rates for all fields

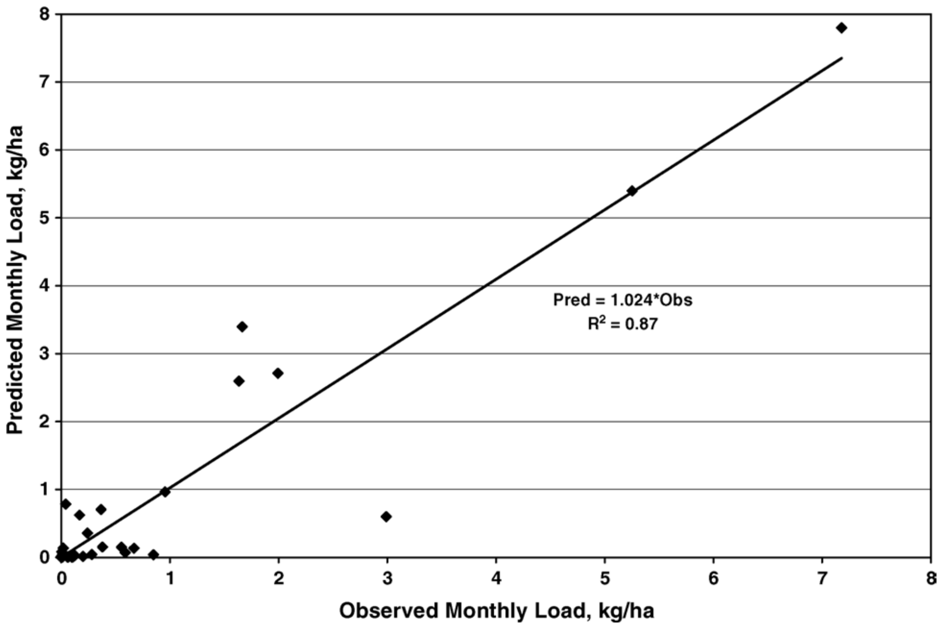

Fig. 9. Observed and predicted monthly nitrate–nitrogen load at S4 for 1998–2000.

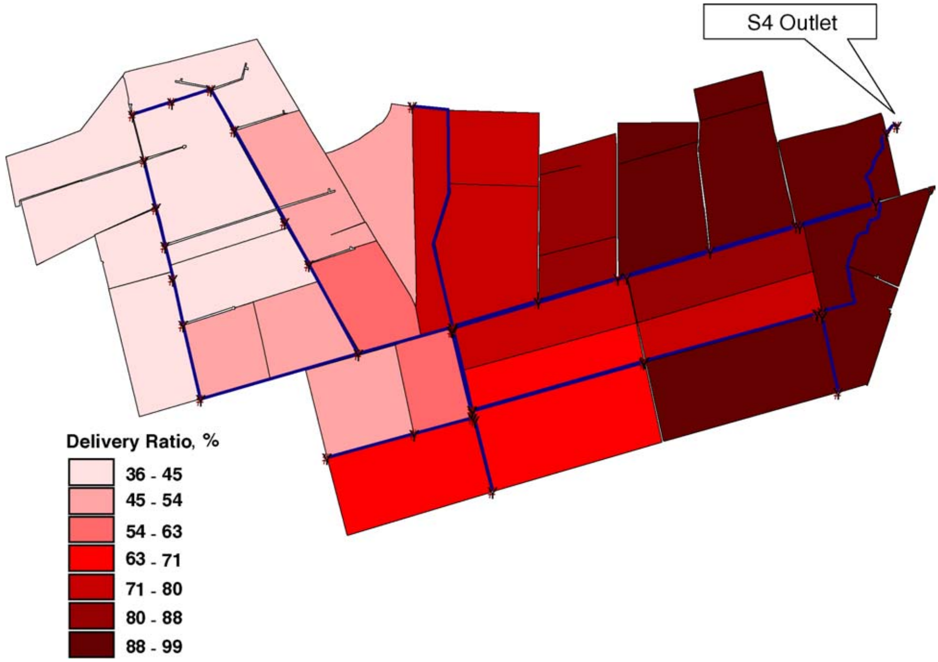

Fig. 10. Average delivery ratios for nitrate–nitrogen based on 5-year DRAINMOD-GIS simulations for S4.

would imply that applying a best management practice or a land use change to reduce loadings at the field edge is nearly thrice as effective on fields near the outlet as on fields farthest from the outlet where the delivery ratio is about 33%.

4.3. Uncertainty analysis

The method used to determine the contribution of the input parameters to the variance in the objective functions (outlet flow, nitrogen load and mean delivery ratio) is the correlation structure between the parameters and the objective functions (Haan and Skaggs, 2003). The contribution, F_i, of an input parameter to the variability of the objective function was determined by

$$F_i = \frac{r_{o,i}^2}{\sum_{i=1}^{p} r_{o,i}^2} \tag{17}$$

where $r_{o,i}$ is the correlation between the objective function and the ith parameter and p is the number of uncertain parameters. Table 7 shows the relative contribution of each parameter to the variability in the objective functions. The variability in stream velocity (VELOC) contributed significantly to the variance in outlet flows, i.e. around 84% of the variance in outlet flows is explained by the variance in stream velocity. Field parameters such as the maximum surface storage (STMAX) and the lateral saturated hydraulic conductivities (CONK1 and CONK2) have less impact on the variability of outlet flows (2–3% of the variance explained). These parameters were found to significantly impact the variability of

Table 7
Relative contribution of each parameter to the variance of objective functions

	Objective functions		
	Annual flow	Annual load	Mean watershed delivery ratio
Parameter	F_i	F_i	F_i
Export concentrations, EXPC	n/a	34.2	26.5
Decay coefficient, KCOEFF	n/a	19.3	26.3
Flow velocity, VELOC	83.6	42.7	43.0
Dispersion, DISP	9.4	0.4	1.0
Surface storage, STMAX	1.7	0.8	0.9
Lateral saturated hydraulic conductivity—Layer 1, CONK1	2.0	1.2	1.2
Lateral hydraulic saturated conductivity—Layer 2, CONK2	3.3	1.4	1.1
Sums	100.0	100.0	100.0

field outflows (Haan and Skaggs, 2003). However, their impact on watershed outflow was modulated by the stream hydraulics.

Three parameters contributed significantly to the variance in outlet load and mean watershed delivery ratio. In addition to the contribution of the canal velocities (VELOC), uncertainty in estimating the field exports (EXPC) and decay coefficient (KCOEFF) contributed significantly to the uncertainty in predicted watershed outlet load and mean watershed delivery ratio. Uncertainty in VELOC, EXPC and KCOEFF contributes 43, 34 and 19%, respectively, to the variance in predicted outlet loads. Forty-three percent of the variability in the mean watershed delivery ratio is accounted for by the variability in stream velocity.

Canal velocities define the travel times within the drainage network, hence, its variability is expected to impact the variability in the delivery ratios. Similarly, variability in the field exports and decay coefficients impacts the variability in outlet loads. Outlet loads are directly related to what goes into the system and the transformations that occurs as drainage water flows through the network. The analysis demonstrates that in order to minimize the uncertainty in the predicted loads at the watershed outlet, accurate characterization of the decay coefficient and field export loads are needed.

5. Summary and conclusion

A watershed scale lumped parameter hydrology and water quality model was developed and applied on a lower coastal plain watershed in North Carolina. The model includes an uncertainty analysis component. Uncertainty analysis was used to determine the impacts of uncertainty in field and network parameters of the model on the predicted outflows and nutrient loading at the outlet of the test watershed. The model, which links DRAINMOD field hydrology and a spatially distributed routing model using a response function, was shown to adequately predict outlet flows and nitrate–nitrogen loads from a lower coastal plain watershed. Uncertainty analysis showed that errors in determining the field parameters such as maximum surface storage and lateral hydraulic conductivity have much less impact on the uncertainty in the prediction of nitrate–nitrogen loads at the outlet, as compared to the field edge. Stream velocities appear to have the greatest impact on predicted outlet loads and mean watershed delivery ratio. Forty-three percent of the variance of the outlet load and delivery ratios is due to the variance of the canal velocities. The relative contributions of the decay coefficient and the export concentrations are also of similar order of magnitude.

For a lumped model, the decay parameter integrates the rates of processes that describe nitrate–nitrogen cycling within the drainage network. Therefore, improving knowledge of this parameter will greatly reduce the uncertainty in nitrate–nitrogen load predictions. Uncertainty, in the field export concentrations also impacts the uncertainty in predicting the outlet loads. The study demonstrates that in addition to an accurate specification of the decay coefficient, field export concentrations need to be quantified accurately to minimize the uncertainty in predicted loads.

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